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W. M. Fawley
M. R. Teague
G. J. Caporaso
S. S. Yu
A. M. Sessler

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Novel Accelerators Employing High-Current Electron Beams: Numerical Simulations†

W. M. Fawley, M. R. Teague, G. J. Caporaso, and S. S. Yu
Lawrence Livermore National Laboratory
Livermore, CA 94550

and

A. M. Sessler
Lawrence Berkeley Laboratory
Berkeley, CA 94720

Abstract

Numerical simulation codes are described which can be used to study the physical phenomena of high-current electron beams employed in some novel accelerator schemes. Examples are given of the study of transverse effects in the free electron laser part of a Two-Beam Accelerator, the study of ion guiding in a Relativistic Klystron, and a study of the acceleration phase of a Collective Implosion Accelerator.

Introduction

Many of the novel acceleration schemes which have been proposed in recent years, and which have attracted considerable attention, involve using an intense electron beam. We think, for example, of the Wake-Field Accelerator,[1] the Two-Beam Accelerator (TBA),[2] the Relativistic Klystron,[3] and the Collective Implosion Accelerator.[4]

Motivated by the desire to more fully understand the various acceleration schemes, and realizing that deep understanding can only be obtained by particle simulation of the intense beam, we have developed the tools for such studies.

In this communication we consider, in turn, three acceleration schemes, and for each describe some of the physical phenomena which are of issue and included in our particle simulations. Then a description is given of the numerical code and, finally, an example is given in which we have studied a "standard case."

We have not, yet, made parametric studies of any scheme (although we believe that that should be done) and, therefore, it is premature to come to any conclusions regarding the relative merits of various schemes on the basis of the work to date.

Two-Beam Accelerator

The TBA is a configuration in which a free-electron laser (FEL) converts energy from a high current, low energy relativistic electron beam into high frequency microwaves, which are then used to power a high gradient accelerating structure. At the end of each wiggler module of the FEL, induction units are used to restore the energy of the high current beam. Typical parameters for the TBA are given in Table I.

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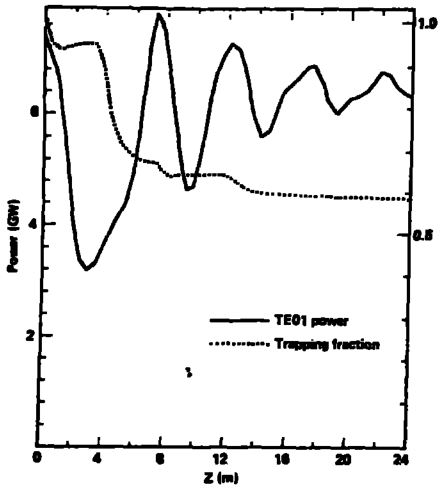
Most numerical investigations[2] of the TBA have been limited to one dimension in which gradients in the transverse direction (x-y) to that of the beam motion are neglected. Although computationally efficient, effects due to non-zero e-beam emittance and mode coupling are necessarily ignored. We have rectified this limitation by adapting the LLNL 2-D FEL simulation code FRED[5] to TBA design studies. For microwave simulation, the code's field solver operates in cartesian geometry and (in this instance) follows the evolution of the TE_{01}, TE_{21} and TM_{21}, TE_{41} and TM_{41}, etc. modes. The electron beam is modeled by macroparticles whose betatron motion is followed in all 3 dimensions. The KMR[6] set of FEL wiggle period-averaged equations together with the paraxial wave equation are used to advance the field and particle quantities. For purposes of TBA modeling, the induction units at the end of each wiggler section are treated as δ-functions in the longitudinal direction that induce a $\Delta\gamma = +4$ for each beam electron, with no change in particle phase ψ. The code follows only one microwave frequency and thus neglects effects such as the Raman instability (sidebands).

A linear taper in field strength was used with a_w dropping from 4.75 to 4.25 over each two-meter section. Weak quadrupolar focusing was used in the wiggle plane direction ($k_q \sim 0.6\ m^{-1}$) as compared with the wiggler field focusing ($k_\beta \sim 2.6\ m^{-1}$). The field equations were modified by the addition of a constant loss term to simulate the power transferred from the FEL waveguide to the high gradient accelerating structure. Longitudinal space charge effects due to bunching were included by assuming a parabolic cross-section for the beam profile.

A short (24 m) simulation of the FEL portion of a TBA was done with FRED. The parameters chosen are given in Table I. In Fig. 1, we show both the fraction of particles trapped in the ponderomotive well and the microwave power in the waveguide as a function of distance down the wiggler. A particle is defined to be untrapped if its phase $|\psi|$ in the ponderomotive well exceeds π. One sees that after a transient phase during which the e-beam becomes bunched, the FEL achieves steady state with a trapping fraction close to 0.6. Since no effort was made to optimize α or the form of the a_w taper during the first 10 m of the device, these results are probably lower limits to the actual trapping fraction achievable in a mature 2-D TBA design. The waveguide power also has a transient phase during which the power oscillates strongly, but by the end of the



24 m the oscillation amplitude has dropped to less than ±10%. Again, a more optimized taper in the first few wiggler sections and/or a lower input power (which would produce a more adiabatic initial bunching of the beam) would strongly reduce the size of the oscillations.

A mode analysis of the FEL power shows that > 98% of the power is in the TE_{01} mode and that essentially no competition exists between the fundamental and higher order modes. This result is similar to results from the LLNL ELF experiments[5] in which significant power appears in higher order modes only at saturation in an untapered wiggler.

Relativistic Klystron

The relativistic Klystron consists of a bunched high current beam of moderate energy (< 100 MeV) going alternatively through sections of induction units for acceleration and cavities for rf power extraction.[3] In order to control beam instabilities and to facilitate beam transport, we propose the use of ion guiding. This may be accomplished, for example, by ionizing a low pressure background gas with a very low current, low energy e-beam (< 100 eV) confined to the center of the pipe by a small magnetic guide field. Guiding by the low-energy e-beam[7] is a variant of the laser-guiding presently employed at ATA, but has the additional potential advantages of being rep-rateable and free from diffraction effects.

A relativistic Klystron has the capability of creating very large power. Arbitrarily we choose 3 GW/m. The wavelength for economic operation of a collider will probably be less than 5 cm; we choose 3 cm for our studies. The gap length has to be a small fraction of a wavelength and the voltage is limited by breakdown considerations. Decoupling of the cavities determines their separation and also the radius of the beam pipe. Together, these considerations determine the beam current.

The cavity parameter R/Q is determined by the geometry. The cavity frequency shift $\Delta\omega/\omega$ and the quality factor Q are chosen to give the desired voltage. In addition, the particle bunch is placed 60° ahead of the peak voltage so as to give longitudinal phase focusing.

Beam energy is determined by the desire to have a rigid beam so that pulse shape is maintained, and also so that longitudinal space charge effects are negligible. The period of the structure, i.e., the distance between re-acceleration induction units is determined by not having the particles lose too much energy. The beam emittance presently achieved on the ATA, together with a reasonable ion (focusing) density permits a beam size much smaller than the beam pipe.

A summary of the parameters of our example is given in Table II.

Sending an intense electron beam through a small resonant structure will excite unstable transverse oscillations due to self-field or wake effects. This instability, known as beam breakup, must be controlled for the scheme to be viable.

For a coasting beam, the growth of the transverse displacement is exponential with z:

$$x = x_o \exp(GQz/2k_\beta\gamma) \quad ,$$

where Q is the quality factor of the mode, k_β is the betatron wavenumber, and G is given by

$$G = (\omega_o Z_\perp/QL_g)(I/I_o) \quad .$$

In this expression, I is the beam current, I_o = 17 kA, $Z_\perp$ is the transverse shunt impedance of the cavity multiplied by Q, L_g is the separation of the cavities, and ω_o is the angular frequency of the dipole mode.

An advantage of laser guiding is its favorable scaling with γ. Compared with solenoids or an alternating quadrupole channel where k_β is proportional to γ^{-1}, a constant density ion channel has a k_β that is proportional to $\gamma^{-1/2}$. A second advantage of ion guiding is the anharmonic nature of the focusing potential; i.e., the focusing force is non-linear.

A non-linear focusing force can lead to phase-mix damping of the beam breakup instability. If the non-linearity is sufficiently great, beam breakup will not grow at all. Qualitatively this must occur when the betatron wavenumber is greater than the inverse growth length of the instability since phase mixing will lead to a damping length on the order of several betatron wavelengths. Quantitatively beam breakup will be suppressed when

$$\delta k_\beta^2 \gamma > \pi G Q$$

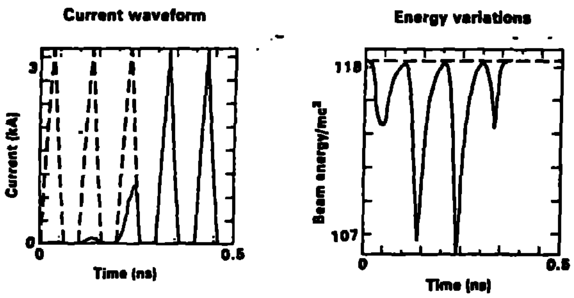
where δ is the fractional spread in k_β^2. This expression can be rearranged to yield a threshold beam current below which beam breakup is suppressed.

$$I < I_o \, (\delta k_\beta^2 \gamma/\pi)/(\omega_o Z_\perp/L_g) \quad .$$

For the parameters given in Table II, the quantity $\omega_o Z_\perp/L_g$ is calculated to be 2-9 cm^{-2} using the method described in Ref. 8. Laser guiding creates a focusing channel where $k_\beta^2\gamma$ is only dependent on the ion density. For the parameters in Table II, $k_\beta^2\gamma$ = 1.6 cm^{-2}.

Combining these expressions, we find beam breakup is suppressed for I < 3δ (kA). Thus an 18% spread in k_β will stabilize a 1 kA beam. This level of non-linearity is easily achieved in practice.

Possible sources of beam degradation include longitudinal space charge effects, differential energy loss to the rf cavities, non-zero longitudinal emittance, and "beam head erosion." Of these processes, we are most concerned with the last. The beam head erodes due to expansion resulting from the non-zero transverse temperature, as well as the loss of beam energy in expelling the secondary electrons. To model these effects, we have constructed a simulation code with an envelope description for the beam, and particle simulation for the secondary electrons. The particular version of the code employed is similar to that described in the section on "The Collective Implosion Accelerator," with specialization to radial electron dynamics only. The dynamics of secondary electron expulsion, beam energy loss, and beam head expansion are self-consistently followed. Figures 2a and 2b give the current and energy waveform after 15 meters of propagation for the parameters given in Table II. The dotted lines in the figures refer to the initial conditions. The loss of the first three pulselets is due to scraping against the pipe wall as the beam head expands. For these parameters, non-zero temperature effects dominate over energy loss. The simulation gives an erosion rate of 10 ns in half a kilometer of travel Reduction of the beam emittance reduces the erosion rate.



2a 2b

The Collective Implosion Accelerator

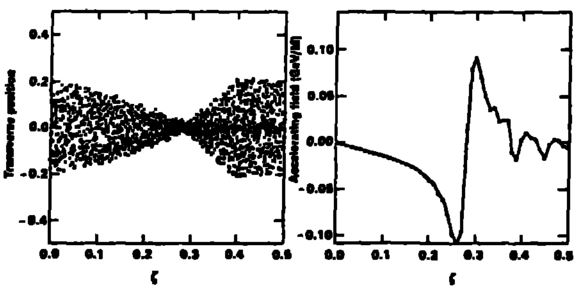
The space charge electric fields occurring in a medium energy, high current (e.g., 50 MeV, 10^4 amperes) electron accelerator can reach values of order 10^6 volts/cm if the electron beam diameter is of order a few millimeters. A scheme to convert these strong radial electric fields into an intense longitudinal electric field that can accelerate an ultra-high-energy electron bunch has recently been proposed.[4]

Briefly, the scheme involves an ion-guided high current charging beam propagating in low density (.01 - 1 mT) gas. The tail of the charging beam is abruptly terminated and is immediately followed by a coaxial high intensity, short duration laser pulse. This ionizes a plasma column whose electrons implode radially inward to neutralize the ion column. The radial currents induce a strong axial electric field (> 100 MV/m) which can then accelerate an ultra-high energy electron bunch.

The critical physics issues of this acceleration scheme are the field gradient obtainable, the maximum length possible for such an accelerator, and the efficiency. The peak E_z spike is determined by the ion column line density, its radius, and by the density of the laser-produced plasma. Briggs[4] has shown that a significant fraction of the beam energy can be converted into potential energy in the ion column. Maximal energy transfer to the high energy beam requires optimizing the geometry of the photoionization plasma including effects of loading by the high energy beam. Ideally the imploding electrons would neutralize the ion column in such a way that their initial implosion creates a high E_z value, while their subsequent repulsion by the high energy beam would leave the imploded electrons and ions only with thermal velocities, essentially all the kinetic energy of the photo-ionization electrons being transferred to the high energy beam.

To simulate the dynamics of the imploding plasma interacting with the ion column and the ultrahigh energy electron beam, we have constructed a simulation code in which the plasma electrons are modeled by a large number of macro-particles (typically 5,000 - 20,000) described by relativistic equations of motion. The electromagnetic fields are computed self-consistently, with sources from the plasma electron current (both radial and axial), from the ions, and from the ultra-high energy electron beam (beam-loading effects are therefore included). We have used the full set of axisymmetric Maxwell's equations, but the field pattern is assumed to move at the speed of light.

Figure 3a shows the imploding plasma electrons. ζ is the distance in cm from the back of the psec laser pulse, which moves from right to left. In Figs. 3a and 3b there are 5×10^{10} electrons in the ultra-high energy beam, which has radius 10^{-3} cm, length $2 \cdot 10^{-2}$ cm and is centered at the center of the negative E_z spike. The ion column has radius 0.20 cm. The ion line density is $2.75 \cdot 10^{12}$/cm, while the plasma electron line density is $1.33 \cdot 10^{11}$/cm.



3a 3b

Figure 3b shows the accelerating field gradient obtained. This is not an optimum case. The gradient may be increased by decreasing the ion column radius and/or increasing the plasma electron line charge density. However, violent plasma oscillations spoil the sharpness of the E spike and limit the density of plasma electrons. Maximally extracting the electrostatic energy of the ion column favors heavy loading with the ultra-high energy beam. However, increasing the number of electrons in the high-energy beam lowers the field gradient. Clearly, many tradeoffs are involved and optimization studies are necessary.

Conclusion

We have developed numerical simulation capability which can be employed to study various novel acceleration schemes based upon the use of intense electron beams. We have demonstrated these codes by studying examples of three schemes; namely the Two-Beam Accelerator, the Relativistic Klystron, and the Collective Implosion Accelerator.

Although as yet we have made no parametric studies of these schemes; we believe that such studies will be very useful in mapping out the acceptable parameter space for any one scheme and, eventually, allowing one to choose amongst the various schemes.

Table I Parameters of a Representative TBA

Beam current I	2400 A
Initial Beam energy γ	40
Beam radius	0.75 cm
Wiggler module length	200 cm
Wiggle period	27 cm
Normalized vector potential a_w	4.75 → 4.25
Waveguide size	5 x 2 cm
Radiation frequency	30 GHz
Initial power	7.5 GW
Loss parameter α (electric field)	.1127 m^{-1}

Table II. Parameters of a Relativistic Klystron

Power extracted	3 GW/m
Wavelength, λ	3 cm
Gap, d	3 mm
Voltage per gaps, V	300 kV
Cavities per period	20
Period of structure	2 meters
Beam pipe radius, r_b	5 mm
Cavity frequency shift, $\Delta\omega/\omega$	0.03
Shunt impedance over quality factor, R/Q	30
Quality factor, Q	13
Average beam current, I	1 kA
Energy of beam, E	60 MeV
Beam emittance (rms), ϵ	1 millirad cm
Beam radius (rms), a	1.0 mm
Background gas pressure (50% ionized)	10^{-4} Torr
Channel radius, a_c	1.0 mm

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